

# Probing Nonstandard Neutrino Physics by Two Identical Detectors with Different Baselines

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(Dated: February 2, 2008)

## Abstract

The Kamioka-Korea two detector system is a powerful experimental setup for resolving neutrino parameter degeneracies and probing CP violation in neutrino oscillation. In this paper, we study sensitivities of this same setup to several nonstandard neutrino physics such as quantum decoherence, tiny violation of Lorentz symmetry, and nonstandard interactions of neutrinos with matter. In most cases, the Kamioka-Korea two-detector setup is more sensitive than the one-detector setup, except for the Lorentz symmetry violation with CPT violation, and the nonstandard neutrino interactions with matter. It can achieve significant improvement on the current bounds on nonstandard neutrino physics.

PACS numbers: 14.60.St,13.15.+g

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## I. INTRODUCTION

Variety of the neutrino experiments, the atmospheric [1], solar [2], reactor [3], and accelerator [4] experiments, have been successful in identifying the neutrino mass induced neutrino oscillation as a dominant mechanism for neutrino disappearances. After passing through the discovery era, the neutrino physics will enter the epoch of precision study, as the CKM phenomenology and a detailed study of CP violation have blossomed in the quark sector. The MNS (Maki-Nakagawa-Sakata) matrix elements will be measured with higher accuracy, including the CP phase(s), and the neutrino properties such as their interactions with matter etc., will be studied in a greater accuracy. During the course of precision studies, it will become natural to investigate nonstandard physics related with neutrinos, which include flavor changing neutral/charged current interactions [5, 6, 7], the effects of quantum decoherence [8, 9, 10] that may possibly arise due to quantum gravity at short distance scale [8], and violation of Lorentz and CPT invariance [11, 12, 13], to name a few.

It is well known that in history of physics experiments based on interference effect played very crucial roles in advancing our understanding of the physical laws. The famous two-slit experiment by Young, Michelson-Morley experiment which demonstrated that there is no ether, Davidson-Germer experiment on electron diffraction,  $K^0 - \overline{K^0}$  oscillation, etc. Likewise, neutrino oscillation experiments may probe another important structure of fundamental physics by observing tiny effects due to CPT violation or quantum decoherence, which may be rooted in quantum gravity. Along with the neutral meson systems ( $K^0 - \overline{K^0}$  and  $B^0 - \overline{B^0}$ ), neutrino oscillations could provide competing and/or complementary informations on those exotic effects. See Ref. [14] for a recent review on this subject.

In a previous work [15, 16] we have introduced and explored in detail the physics potential of the Kamioka-Korea two detector setting which receive an intense neutrino beam from J-PARC. We have demonstrated that the setting is powerful enough to resolve all the eight-fold parameter degeneracy [17, 18, 19], if  $\theta_{13}$  is in reach of the next generation accelerator [20, 21] and the reactor experiments [22, 23]. The degeneracy includes the parameters  $\theta_{13}$ ,  $\delta$  and octant of  $\theta_{23}$ , and it is doubled by the ambiguity which arises due to the unknown sign of  $\Delta m_{31}^2$ . The detector in Korea plays a decisive role to lift the last one. For related works on Kamioka-Korea two detector complex, see, for example, [24, 25, 26, 27].

The Kamioka-Korea identical two detector setting is a unique apparatus for studying nonstandard physics (NSP). As will be elaborated in Sec. II the deviation from the expectation by the standard mass-induced oscillation can be sensitively probed by comparing yields at the intermediate (Kamioka) and the far (Korea) detectors. In this paper, we aim at exploring physics potential of the Kamioka-Korea setting in a systematic way. By this we mean that we examine several NSP effects in a single framework by concentrating on  $\nu_\mu - \nu_\tau$  subsystem in the standard three-flavor mixing scheme, and focus on  $\nu_\mu$  disappearance measurement. Though limited framework, it will allow us to treat the problem in a coherent fashion.

In analyzing nonstandard physics in this paper, we aim at demonstrating the powerfulness of the Kamioka-Korea identical two detector setting, compared to other settings. For this purpose, we systematically compare the results obtained with the following three settings:

- Kamioka-Korea setting: Two identical detectors one at Kamioka and the other in Korea each 0.27 Mton
- Kamioka-only setting: A single 0.54 Mton detector at Kamioka

- Korea-only setting: A single 0.54 Mton detector at somewhere in Korea.

Among the cases we have examined Kamioka-Korea setting always gives the best sensitivities, apart from two exceptions of violation of Lorentz invariance in a CPT violating manner, and the nonstandard neutrino interactions with matter. Whereas, the next best case is sometimes Kamioka-only or Korea-only settings depending upon the problem.

This paper is organized as follows. In Sec. II, we illustrate how we can probe nonstandard physics with Kamioka-Korea two detector setting, with a quantum decoherence as an example of nonstandard neutrino physics. In Sec. III, we describe the statistical method which is used in our analyses in the following sections. In Sec. IV, we discuss quantum decoherence. In Sec. V, we discuss possible violation of Lorentz invariance. In Sec. VI, we discuss non-standard neutrino matter interactions, and the results of study is summarized in Sec. VII.

## II. PROBING NON-STANDARD PHYSICS WITH KAMIOKA-KOREA TWO DETECTOR SETTING

In this section, we describe how we proceed in the following sections. For the purpose of illustration, we consider quantum decoherence (QD) as nonstandard neutrino physics. In this case, the  $\nu_\mu$  survival probability (and the  $\bar{\nu}_\mu$  survival probability assuming CPT invariance in the presence of QD) is given by [9, 10],

$$P(\nu_\mu \rightarrow \nu_\mu) = P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu) = 1 - \frac{1}{2} \sin^2 2\theta \left[ 1 - e^{-\gamma(E)L} \cos\left(\frac{\Delta m^2 L}{2E}\right) \right], \quad (1)$$

where we consider the case  $\gamma(E) = \gamma/E$  (see Sec. IV where we consider also the cases of  $\gamma(E)$  which has other energy dependences). Then one can calculate the number of  $\nu_\mu$  and  $\bar{\nu}_\mu$  events observed at two detectors placed at Kamioka (with baseline of 295 km) and Korea (with baseline of 1050 km), using the above survival probability and the neutrino beam profiles. For simplicity, let us consider the number of observed neutrino events both at Kamioka and Korea, for each energy bin (with 50 MeV width) from  $E_\nu = 0.2$  GeV upto  $E_\nu = 1.4$  GeV. In Fig. 1, we show the  $\nu_\mu$  event spectra at detectors located at Kamioka and Korea for the pure oscillation  $\gamma = 0$  (the left column) and the oscillation plus QD with two different QD parameters,  $\gamma = 1 \times 10^{-4}$  GeV/km (the middle column) and  $\gamma = 2 \times 10^{-4}$  GeV/km (the right column)<sup>1</sup>. One finds that spectra change for non-vanishing  $\gamma$ . Especially we point out that the spectra changes are different between detectors at Kamioka and Korea due to the different  $L/E$  values at the two positions.

Assuming the actual data at Kamioka and Korea are given (or well described) by the pure oscillation with  $\sin^2 2\theta = 1$  and  $\Delta m^2 = 2.5 \times 10^{-2}$  eV<sup>2</sup>, we could claim that  $\gamma = 1 \times 10^{-4}$  GeV/km (shown in the middle column), for example, would be inconsistent with the data. One can make this kind of claim in a more proper and quantitative manner using the  $\chi^2$  analysis, which is described in details in the following section.

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<sup>1</sup> In order to convert this  $\gamma$  in unit of GeV/km to  $\gamma$  defined in Eq. (5), one has to multiply  $0.197 \times 10^{-18}$ .

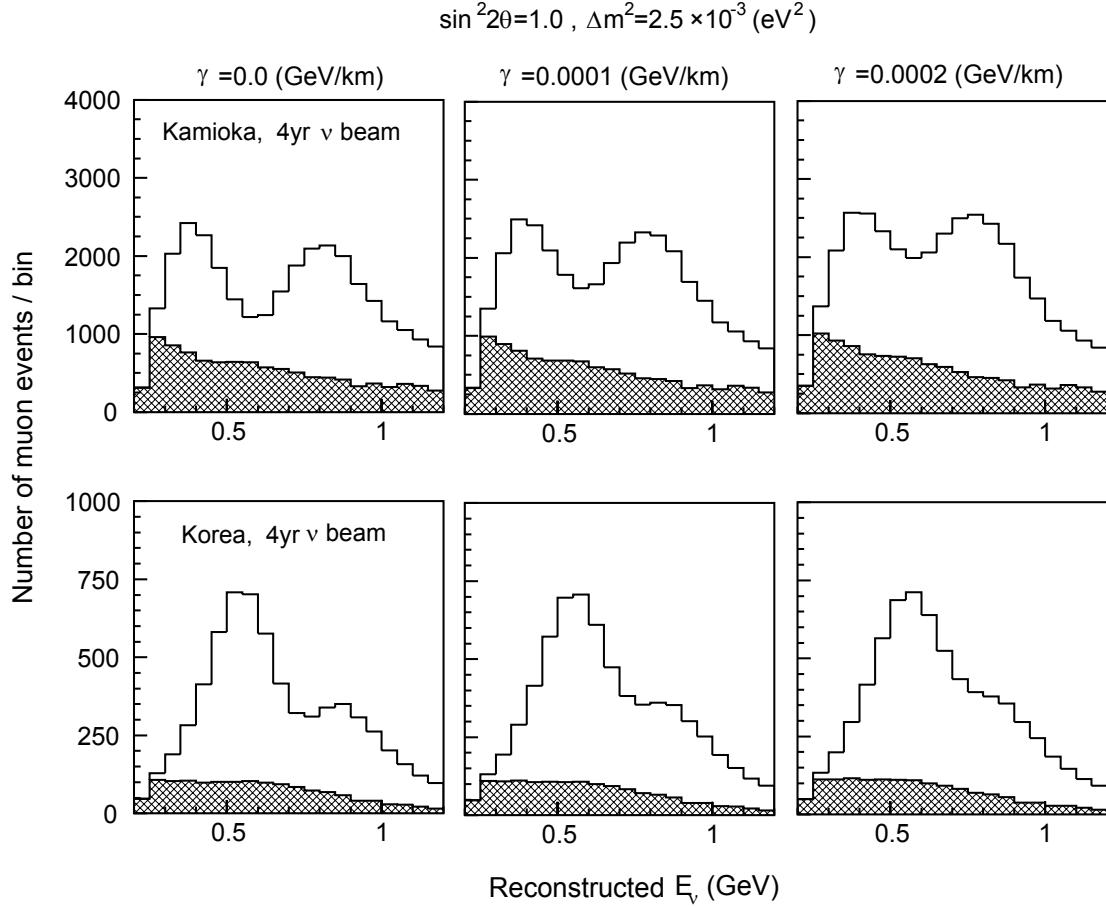


FIG. 1: Event spectra of neutrinos at Kamioka (the top panel) and Korea (the bottom panel) for  $\gamma = 0$  (the left column),  $1 \times 10^{-4}$  GeV/km (the middle column), and  $\gamma = 2 \times 10^{-4}$  GeV/km (the right column). The hatched areas denote the contributions from non-quasi-elastic events.

### III. ANALYSIS METHOD

In studying nonstandard physics through neutrino oscillations we restrict ourselves into the  $\nu_\mu - \nu_\tau$  subsystem, rather than dealing with the full three generation problem. The reason is partly technical and partly physics motivated. The technical reason for truncation is to simplify analysis in a manner not to spoil the most important features of the problem. First of all,  $\nu_\mu \rightarrow \nu_\mu$  and  $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$  probabilities do not depend much on the yet unknown parameters, namely,  $\theta_{13}$ , CP phase and the sign of  $\Delta m_{31}^2$ . Second, in most cases the earth matter effect is a sub-leading effect in the  $\nu_\mu - \nu_\tau$  subsystem so that by restricting to the subsystem we need not to worry about complications due to the matter effect. Moreover, many of the foregoing analyses were carried out under the truncated framework. By working under the same approximation the comparison between ours and the existing results becomes much simpler. Thus, the  $\Delta m^2$  which will appear in neutrino oscillation probabilities in the following sections is meant to be  $\Delta m^2 \equiv \Delta m_{32}^2 = m_3^2 - m_2^2$ .  $\theta$  will be a mixing angle in the unitary matrix diagonalizing the Hamiltonian in the  $\nu_\mu - \nu_\tau$  subsystem, which is essentially equal to  $\theta_{23}$ .

### A. Method of statistical analysis

In order to understand the sensitivity of the experiment with the two detector system at 295 km (Kamioka) and 1050 km (Korea), we carry out a  $\chi^2$  analysis. In the present analysis, we only included  $\nu_\mu$  and  $\bar{\nu}_\mu$  disappearance channels. In short, the definition of the statistical procedure is similar to the one used in [16] excluding the electron events. The assumption on the experimental setting is also identical to that of the best performance setting identified in Ref. [15]. Namely, 0.27 Mton fiducial masses for the intermediate site (Kamioka, 295 km) and the far site (Korea, 1050 km). For the reference, we also consider 0.54 Mton detector for Kamioka or Korea only. The neutrino beam is assumed to be 2.5 degree off-axis one produced by the upgraded J-PARC 4 MW proton beam. It is assumed that the experiment will continue for 8 years with 4 years of neutrino and 4 years of anti-neutrino runs.

We use various numbers and distributions available from references related to T2K [28], in which many of the numbers are updated after the original proposal [20]. Here, we summarize the main assumptions and the methods used in the  $\chi^2$  analysis. We use the reconstructed neutrino energy for single-Cherenkov-ring muon events. The resolution in the reconstructed neutrino energy is 80 MeV for quasi-elastic (QE) events. We take  $\Delta m^2 = 2.5 \times 10^{-3} \text{ eV}^2$  and  $\sin^2 2\theta_{23} = 1.0$  for our reference value. However, whenever we expect that there is a correlation between the expected sensitivity to new physics and the oscillation parameters, we scan  $\Delta m_{31}^2$  between 2.0 and  $3.0 \times 10^{-3} \text{ eV}^2$  and  $\sin^2 2\theta_{23}$  between 0.9 and 1.0. The shape of the energy spectrum for the anti-neutrino beam is assumed to be identical to that of the neutrino beam. The event rate for the anti-neutrino beam in the absence of neutrino oscillations is smaller by a factor of 3.4 due mostly to the lower neutrino interaction cross sections and partly to the slightly lower flux. In addition, the contamination of the wrong sign muon events is higher in the anti-neutrino beam.

We stress that in the present setting the detectors located in Kamioka and in Korea are not only identical but also receive neutrino beams with essentially the same energy distribution (due to the same off-axis angle of 2.5 degree) in the absence of oscillations. However, it was realized recently that, due to a non-circular shape of the decay pipe of the J-PARC neutrino beam line, the flux energy spectra viewed at detectors in Kamioka and in Korea are expected to be slightly different even at the same off-axis angle, especially in the high-energy tail of the spectrum [29]. The possible difference between fluxes in the intermediate and the far detectors is taken into account as a systematic error in the present analysis.

We compute neutrino oscillation probabilities by numerically integrating neutrino evolution equation under the constant density approximation. The average density is assumed to be 2.3 and  $2.8 \text{ g/cm}^3$  for the matter along the beam line between the production target and Kamioka and between the target and Korea, respectively [15]. We assume that the number of electron with respect to that of nucleons to be 0.5 to convert the matter density to the electron number density.

The statistical significance of the measurement considered in this paper was estimated by using the following definition of  $\chi^2$ :

$$\chi^2 = \sum_{k=1}^4 \left( \sum_{i=1}^{20} \frac{(N(\mu)_i^{\text{obs}} - N(\mu)_i^{\text{exp}})^2}{\sigma_i^2} \right) + \sum_{j=1}^4 \left( \frac{\epsilon_j}{\tilde{\sigma}_j} \right)^2, \quad (2)$$

where

$$N(\mu)_i^{\text{exp}} = N_i^{\text{non-QE}} \cdot (1 + \sum_{j=1,3,4} f(\mu)_j^i \cdot \epsilon_j) + N_i^{\text{QE}} \cdot (1 + \sum_{j=1,2,4} f(\mu)_j^i \cdot \epsilon_j) . \quad (3)$$

In Eq. (2),  $N(\mu)_i^{\text{obs}}$  is the number single-ring muon events to be observed for the given (oscillation) parameter set, and  $N(\mu)_i^{\text{exp}}$  is the expected number of events for the assumed parameters in the  $\chi^2$  analysis.  $k = 1, 2, 3$  and  $4$  correspond to the four combinations of the detectors in Kamioka and in Korea with the neutrino and anti-neutrino beams, respectively. The index  $i$  represents the reconstructed neutrino energy bin for muons. The energy range for the muon events covers from 200 to 1200 MeV. Each energy bin has 50 MeV width.  $\sigma_i$  denotes the statistical uncertainties in the expected data. The second term in the  $\chi^2$  definition collects the contributions from variables which parameterize the systematic uncertainties in the expected number of signal and background events.

$N_i^{\text{non-QE}}$  are the number of non-quasi-elastic muon events for the  $i^{\text{th}}$  bin whereas  $N_i^{\text{QE}}$  are the number of quasi-elastic muon events. We treat the non-quasi-elastic and quasi-elastic muon events separately, since the neutrino energy cannot be properly reconstructed for non-quasi-elastic events. Both  $N_i^{\text{QE}}$  and  $N_i^{\text{non-QE}}$  depend on neutrino (oscillation) parameters but in a different way, namely, the former (latter) being affected in direct (indirect) manner and hence dependence is strong (weak) as we can see from the solid histogram ( $N_i^{\text{QE}} + N_i^{\text{non-QE}}$ ) and the hatched region ( $N_i^{\text{non-QE}}$ ) in Fig. 1. The key to high sensitivity to NSP is the different oscillation parameter dependence between Kamioka and the Korean detectors due to different baselines. The uncertainties in  $N_i^{\text{non-QE}}$  and  $N_i^{\text{QE}}$  are represented by 4 parameters  $\epsilon_j$  ( $j = 1$  to  $4$ ).

During the fit, the values of  $N(\mu)_i^{\text{exp}}$  are recalculated for each choice of the (oscillation) parameters which are varied freely to minimize  $\chi^2$ , and so are the systematic error parameters  $\epsilon_j$ . The parameter  $f(\mu)_j^i$  represents the fractional change in the predicted event rate in the  $i^{\text{th}}$  bin due to a variation of the parameter  $\epsilon_j$ . We assume that the experiment is equipped with a near detector which measures the un-oscillated muon spectrum. The uncertainties in the absolute normalization of events are assumed to be 5% ( $\tilde{\sigma}_1=0.05$ ). The functional form of  $f(\mu)_2^i = (E_{\nu}(\text{rec}) - 800 \text{ MeV})/800 \text{ MeV}$  is used to define the uncertainty in the spectrum shape for quasi-elastic muon events ( $\tilde{\sigma}_2=0.05$ ) [16].

The uncertainty in the separation of quasi-elastic and non-quasi-elastic interactions in the muon events is assumed to be 20% ( $\tilde{\sigma}_3=0.20$ ). In addition, for the number of events in Korea, the possible flux difference between Kamioka and Korea is taken into account in  $f(\mu)_4^i$ . The predicted flux difference [29] is simply assumed to be the 1  $\sigma$  uncertainty in the flux difference ( $\tilde{\sigma}_4$ ).

Finally, in this work, the sensitivity at 90% (99 %) confidence level (CL) is defined by

$$\Delta\chi^2 \equiv \chi^2_{\text{min}}(\text{osc. + nonstandard physics}) - \chi^2_{\text{min}}(\text{osc.}) \geq 2.71 \text{ (6.63)},$$

corresponding to the one degree of freedom. Similarly, the criterion for the two degrees of freedom is  $\Delta\chi^2 \geq 4.61$  (9.21).

#### IV. QUANTUM DECOHERENCE (QD)

Study of “quantum decoherence” is based on a hypothesis that somehow there may be a loss of coherence due to environmental effect or quantum gravity and space-time foam,

etc [8]. We do not discuss the origin of decoherence in this paper, but concentrate on how this effect can be probed by the Kamioka-Korea setting (this statement also applies to other nonstandard physics considered in this paper). For previous analyses of decoherence in neutrino experiments, see e.g., [9, 30, 31, 32, 33]. As discussed in Sec. I we consider the  $\nu_\mu - \nu_\tau$  two-flavor system. Since the matter effect is a sub-leading effect in this channel we employ vacuum oscillation approximation in this section. The two-level system in vacuum in the presence of quantum decoherence can be solved to give the  $\nu_\mu$  survival probability [9, 10]:

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \frac{1}{2} \sin^2 2\theta \left[ 1 - e^{-\gamma(E)L} \cos \left( \frac{\Delta m^2 L}{2E} \right) \right], \quad (4)$$

where  $\gamma(E) > 0$  is the parameter which controls the strength of decoherence effect. Notice that the conventional two-flavor oscillation formula is reproduced in the limit  $\gamma(E) \rightarrow 0$ . Since the total probability is still conserved in the presence of QD, the relation  $P(\nu_\mu \rightarrow \nu_\tau) = 1 - P(\nu_\mu \rightarrow \nu_\mu)$  holds. A similar expression holds for the anti-neutrino survival probability with possible different decoherence index  $\bar{\gamma}(E)$ . We assume CPT invariance in this section so that  $\bar{\gamma}(E) = \gamma(E)$ ; Then, the  $\bar{\nu}_\mu$  survival probability is the same as in (4) follows.

Unfortunately, nothing is known about the energy dependence of  $\gamma(E)$ . Therefore, we examine, following [9], several typical cases of energy dependence of  $\gamma(E)$ :

$$\gamma(E) = \gamma \left( \frac{E}{\text{GeV}} \right)^n \quad (\text{with } n = 0, 2, -1) \quad (5)$$

In this convention, the overall constant  $\gamma$  has a dimension of energy or  $(\text{length})^{-1}$ , irrespective of the values of the exponent  $n$ . We will use  $\gamma$  in GeV unit in this section. In the following three subsections, we analyze three different energy dependences,  $n = 0, -1, 2$  one by one.

### A. Case of $\frac{1}{E}$ dependence of $\gamma(E)$

First, we examine the case with  $\frac{1}{E}$  dependence of  $\gamma(E)$ . In Fig. 2, we show the correlations between  $\gamma$  and  $\sin^2 2\theta$  at three experimental setups for the case where the input values are  $\gamma = 0$ ,  $\Delta m^2 = 2.5 \times 10^{-3} \text{ eV}^2$  and  $\sin^2 2\theta = 0.96$ . We immediately find that there are strong correlations between  $\sin^2 2\theta$  and  $\gamma$  for the Kamioka-only and Korea-only setups. We also note that the slope of the correlation for the Kamioka-only setup is different from that for the Korea-only setup. Therefore the Kamioka-Korea setup can give a stronger bound than each experimental setup. This advantage can be seen in Fig. 3, where we present the sensitivity regions of  $\gamma$  as a function of  $\sin^2 2\theta$  (left panel) and  $\Delta m^2$  (right panel). Note that the sensitivity to  $\gamma$  in the Kamioka-Korea setting is better than the Korea-only and the Kamioka-only settings by a factor greater than 3 and 6, respectively.

### B. Case of energy independent $\gamma(E)$

Next, we examine the case of energy independent  $\gamma$ ,  $\gamma(E) = \gamma = \text{constant}$ . Repeating the same procedure as before, we find that the sensitivity to  $\gamma$  in the Kamioka-Korea setting is better than the Korea-only and the Kamioka-only settings by a factor greater than 3 and 8, respectively, as summarized in Table I.

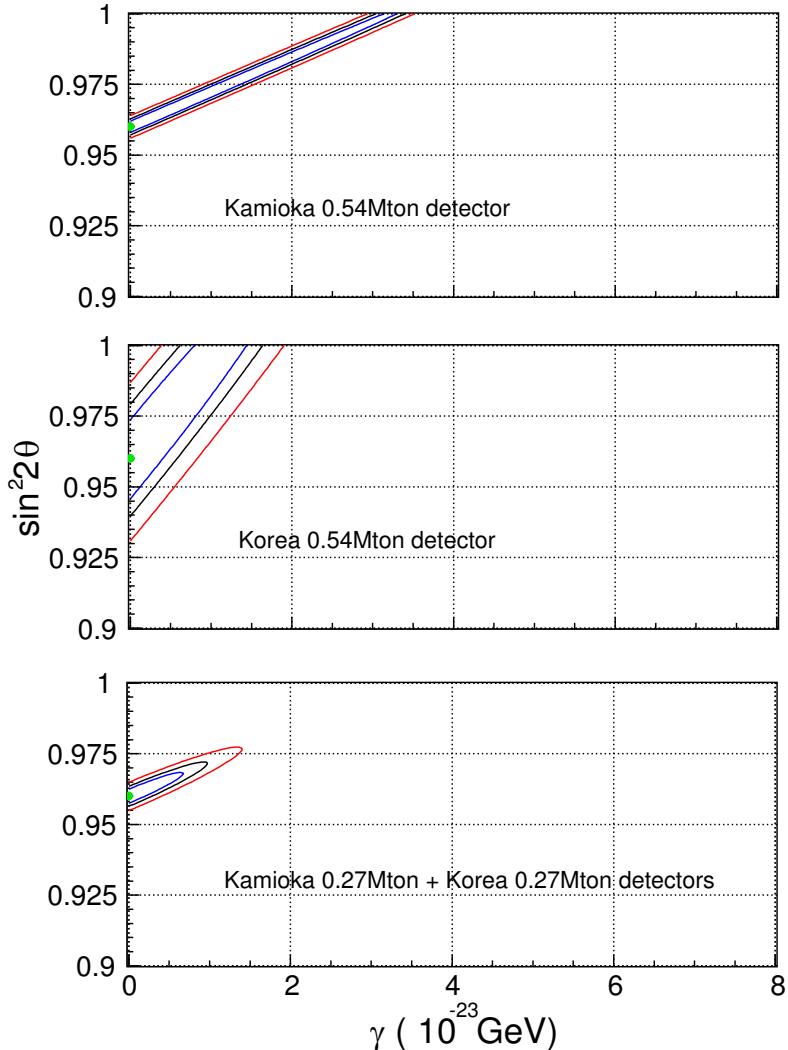


FIG. 2: The correlations between  $\gamma$  and  $\sin^2 2\theta$  for three experimental setups we consider: Kamioka-only, Korea-only and Kamioka-Korea. Blue, black and red curves represent the contours for 68% , 90% and 99% CL for two degrees of freedom. Input values are  $\gamma = 0$ ,  $\Delta m^2 = 2.5 \times 10^{-3}$  eV<sup>2</sup> and  $\sin^2 2\theta = 0.96$ .

### C. Case of $E^2$ dependence of $\gamma(E)$

Finally, we examine the case with  $E^2$  dependence of  $\gamma$ . The qualitative features of the sensitivities are similar to those of the previous two cases. The result is that the sensitivity to  $\gamma$  in the Kamioka-Korea setting is better than the Korea-only and the Kamioka-only settings by a factor greater than 3 and 5, respectively.

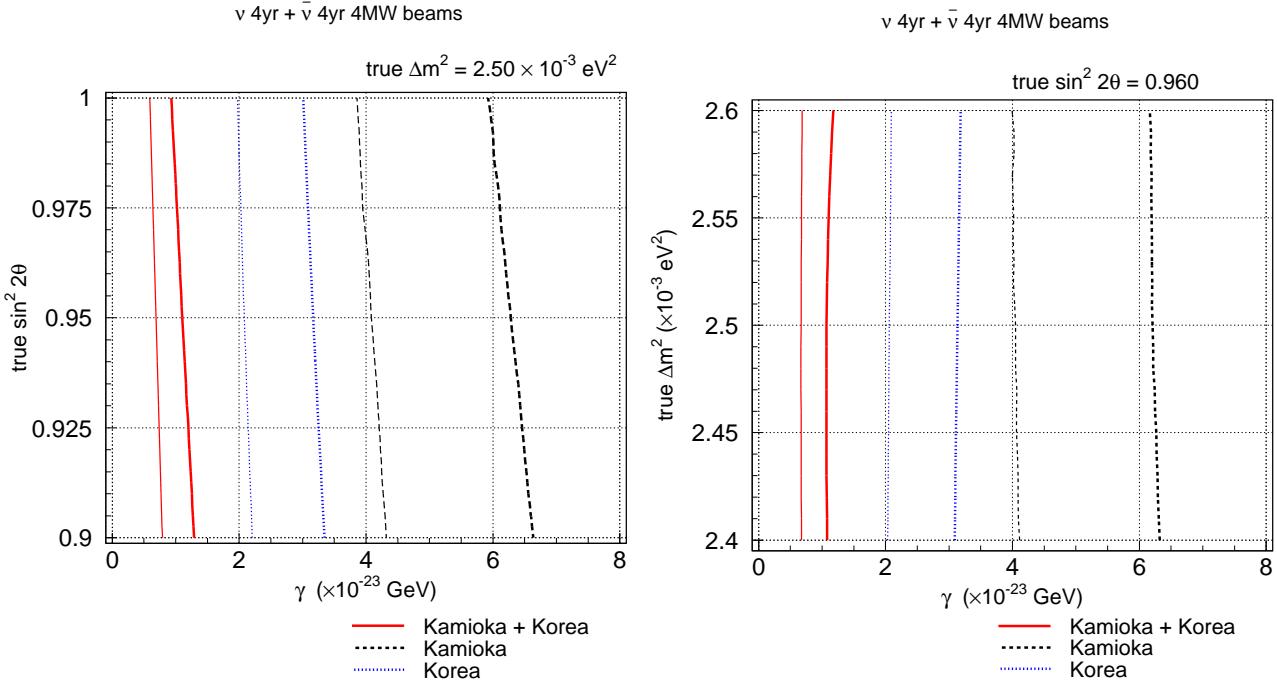


FIG. 3: The sensitivity to  $\gamma$  as a function of the true (input) value of  $\sin^2 2\theta \equiv \sin^2 2\theta_{23}$  (left panel) and  $\Delta m^2 \equiv \Delta m_{32}^2$  (right panel) for the case of  $1/E$  dependence of  $\gamma(E)$ . The red solid lines are for Kamioka-Korea setting with each 0.27 Mton detector, while the dashed black (dotted blue) lines are for Kamioka (Korea) only setting with 0.54 Mton detector. The thick and the thin lines are for 99% and 90% CL, respectively. 4 years of neutrino plus 4 years of anti-neutrino running are assumed. In obtaining the results shown in the left and right panel, the input value of  $\Delta m_{32}^2$  is taken as  $+2.5 \times 10^{-3} \text{ eV}^2$  (with positive sign indicating the normal mass hierarchy) and that of  $\sin^2 2\theta_{23}$  as 0.96, respectively.

#### D. Comparison between sensitivities of Kamioka-Korea setting and the existing bound on $\gamma$

In Table I, we list, for the purpose of comparison, the upper bounds on  $\gamma$  at 90% CL obtained by analyzing the atmospheric neutrino data in [9]<sup>2</sup>. We summarize in the table the bounds on  $\gamma$  at 90% CL achievable by the Kamioka-only, the Korea-only and the Kamioka-Korea settings. We use the same ansatz as in [9] for parameterizing the energy dependence of  $\gamma(E)$ ,  $n = 0, -1$  and 2.

In the case of  $\frac{1}{E}$  dependence of  $\gamma(E)$ , all three settings can improve the current bound almost by two orders of magnitude. Note that the best case (Kamioka-Korea) is a factor of 6 better than the Kamioka-only case. This case demonstrates clearly that the two-detector setup is more powerful than the Kamioka-only setup. We notice that in the case of energy independence of  $\gamma(E)$ , Kamioka-Korea two detector setting can improve the current bound

<sup>2</sup> We do not quote the bounds on  $\gamma$  obtained from solar and KamLAND neutrinos, since they are derived from  $\nu_e \rightarrow \nu_e$  [34]. In this case, the neutrino energy is quite low, so that the constraint for  $n = -1$  becomes quite strong.

Ansats for $\gamma(E)$	Current bound (GeV)	Kamioka-only (GeV)	Korea-only (GeV)	Kamioka-Korea (GeV)
$\gamma(E) = \gamma$ (const.)	$< 3.5 \times 10^{-23}$	$< 8.7 \times 10^{-23}$	$< 3.2 \times 10^{-23}$	$< 1.1 \times 10^{-23}$
$\gamma(E) = \gamma/E(\text{GeV})$	$< 2.0 \times 10^{-21}$	$< 4.0 \times 10^{-23}$	$< 2.0 \times 10^{-23}$	$< 0.7 \times 10^{-23}$
$\gamma(E) = \gamma(E(\text{GeV}))^2$	$< 0.9 \times 10^{-27}$	$< 9.2 \times 10^{-23}$	$< 6.0 \times 10^{-23}$	$< 1.7 \times 10^{-23}$

TABLE I: Presented are the upper bounds on decoherence parameters  $\gamma$  defined in (5) for three possible values of  $n$ . The current bounds are based on [9] and are at 90% CL. The sensitivities obtained by this study are also at 90% CL and correspond to the true values of the parameters  $\Delta m^2 = 2.5 \times 10^{-3} \text{ eV}^2$  and  $\sin^2 2\theta_{23} = 0.96$ .

by a factor of  $\sim 3$ .

In the case of  $E^2$  dependence of  $\gamma(E)$  the situation is completely reversed; The bound imposed by the atmospheric neutrino data surpasses those of our three settings by almost  $\sim 4$  orders of magnitude. Because the spectrum of atmospheric neutrinos spans a wide range of energy which extends to 100-1000 GeV, it gives much tighter constraints on the decoherence parameter for quadratic energy dependence of  $\gamma(E)$ . In a sense, the current Super-Kamiokande experiment is already a powerful neutrino spectroscope with a very wide energy range, and could be sensitive to nonstandard neutrino physics that may affect higher energy neutrinos such as QD with  $\gamma(E) \sim E^2$  or Lorentz symmetry violation (see Sec. V for more details).

## V. VIOLATION OF LORENTZ INVARIANCE

In the presence of Lorentz symmetry violation by a tiny amount, neutrinos can have both velocity mixings and the mass mixings, both are CPT conserving [11]. Also there could be CPT-violating interactions in general [11, 12, 13]. Then, the energy of neutrinos with definite momentum in ultra-relativistic regime can be written as

$$\frac{mm^\dagger}{2p} = cp + \frac{m^2}{2p} + b, \quad (6)$$

where  $m^2$ ,  $c$ , and  $b$  are  $3 \times 3$  hermitian matrices, and the three terms represent, in order, the effects of velocity mixing, mass mixing, and CPT violation [12]. The energies of neutrinos are eigenvalues of (6), and the eigenvectors give the “mass eigenstates”. Notice that while  $c$  is dimensionless quantity,  $b$  has dimension of energy. For brevity, we will use GeV unit for  $b$ .

Within the framework just defined above it was shown by Coleman and Glashow [12] that the  $\nu_\mu$  disappearance probability in vacuum can be written as

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\Theta \sin^2 (\Delta L/4) \quad (7)$$

where the “mixing angle”  $\Theta$  and the phase factor  $\Delta$  depend upon seven parameters apart from energy  $E$ :

$$\begin{aligned} \Delta \sin 2\Theta &= \Delta m^2 \sin 2\theta_m/E + 2\delta b e^{i\eta} \sin 2\theta_b + 2\delta c e^{i\eta'} E \sin 2\theta_c, \\ \Delta \cos 2\Theta &= \Delta m^2 \cos 2\theta_m/E + 2\delta b \cos 2\theta_b + 2\delta c E \cos 2\theta_c. \end{aligned} \quad (8)$$

As easily guessed what is relevant in neutrino oscillation is the difference in mass squared, and  $b$  and  $c$  between two mass eigenstates,  $\delta b \equiv b_2 - b_1$  and  $\delta c \equiv c_2 - c_1$ , where  $c_{i=1,2}$  and  $b_{i=1,2}$  are the eigenvalues of the matrix  $c$  and  $b$ . The angles  $\theta_m$ ,  $\theta_b$  and  $\theta_c$  appear in the unitary matrices which diagonalize the matrices  $m^2$ ,  $b$ , and  $c$ , respectively. There are also two phases  $\eta$  and  $\eta'$  that cannot be rotated away by field redefinition. We work in the convention in which  $\cos 2\theta_m$  and  $\cos 2\theta_b$  are positive, and  $\Delta m^2 \equiv m_2^2 - m_1^2$ ,  $\delta b \equiv b_2 - b_1$  and  $\delta c \equiv c_2 - c_1$  can have either signs.

The survival probability for the anti-neutrino is obtained by the following substitution:

$$\delta c \rightarrow \delta c, \quad \delta b \rightarrow -\delta b \quad (9)$$

The difference in the sign changes signify the CPT conserving vs. CPT violating nature of  $c$  and  $b$  terms.

The two-flavor oscillation given by (7) and (8) is a too complicated system for full analysis. Therefore, we make some simplifications in our analysis. We restrict ourselves into the case  $\theta_m = \theta_b = \theta_c \equiv \theta$  and  $\eta = \eta' = 0$ , for which one recovers the case treated in [35]:

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta \sin^2 \left[ L \left( \frac{\Delta m^2}{4E} + \frac{\delta b}{2} + \frac{\delta c E}{2} \right) \right], \quad (10)$$

which still depends on 4 parameters,  $\theta$ ,  $\Delta m^2$ ,  $\delta b$  and  $\delta c$ . One has a similar expression for  $\bar{\nu}_\mu$  with  $\delta b \rightarrow -\delta b$ . As pointed out in [36], the analysis for violation of Lorentz invariance with  $\delta c$  term is equivalent to testing the equivalence principle [37]. The oscillation probability in (10) looks like the one for conventional neutrino oscillations due to  $\Delta m^2$ , with small corrections due to the Lorentz symmetry violating  $\delta b$  and  $\delta c$  terms. In this sense, it may be the most interesting case to examine as a typical example with the Lorentz symmetry violation. Note that the sign of  $\delta b$  and  $\delta c$  can have different effects on the survival probabilities, so that the bounds on  $\delta b$  and  $\delta c$  could depend on their signs, although we will find that the difference is rather small.

For ease of analysis and simplicity of presentation, we further restrict our analysis to the case of either  $\delta b = 0$  and  $\delta c \neq 0$ , or  $\delta b \neq 0$  and  $\delta c = 0$ . Notice that the former is CPT conserving while the latter is CPT violating.

### A. Case with $\delta b = 0$ and $\delta c \neq 0$ (CPT conserving)

We first examine violation of Lorentz invariance in the case of  $\delta b = 0$  and  $\delta c \neq 0$ . In Fig. 4 we present the region of allowed values of  $\delta c$  as a function of  $\sin^2 2\theta$  (left panel) and  $\Delta m^2$  (right panel). Unlike the case of quantum decoherence, the sensitivities to  $\delta c$  achieved by the Kamioka-Korea setting is slightly better than those of the Korea-only and the Kamioka-only settings but not so much. The sensitivity is weakly correlated to  $\theta$ , and the best sensitivity is achieved at the maximal  $\theta$ . There is almost no correlation to  $\Delta m^2$ .

### B. Case with $\delta c = 0$ and $\delta b \neq 0$ (CPT violating)

The allowed regions with violation of Lorentz invariance in the case of  $\delta c = 0$  and  $\delta b \neq 0$  presented in Fig. 5 have several unique features. First of all, unlike the system with decoherence, the sensitivity is greatest in the Kamioka-only setting, though the one by the

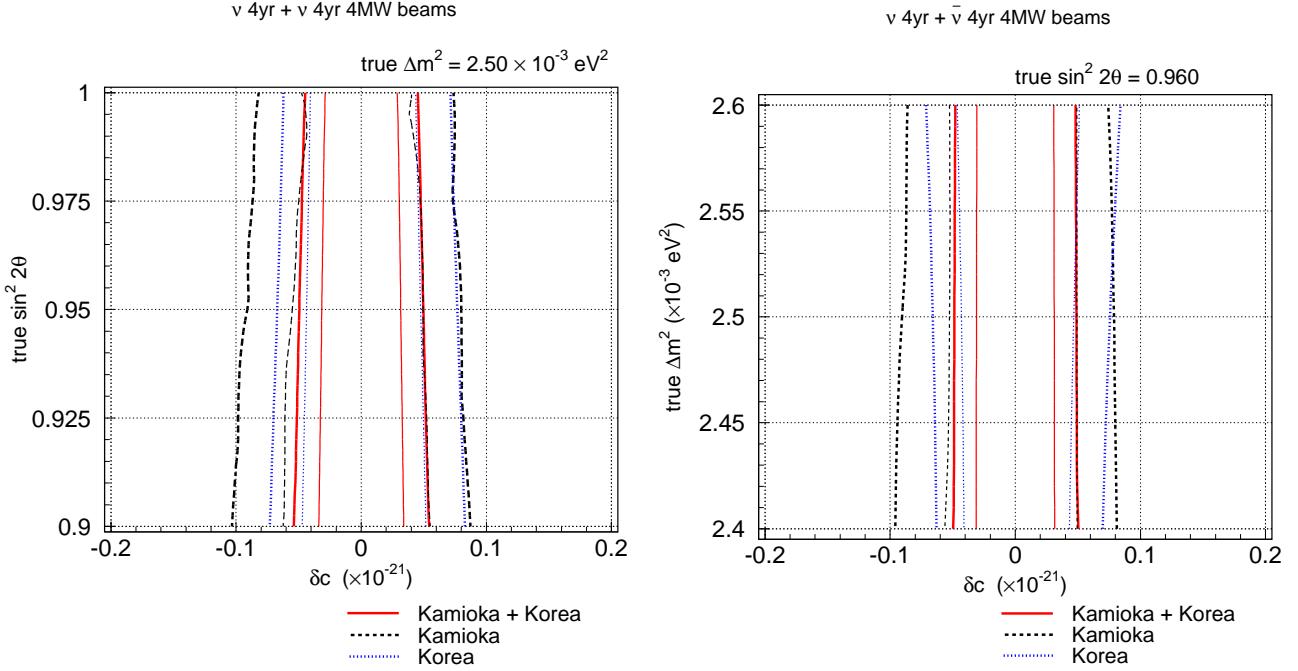


FIG. 4: The sensitivities to  $\delta c$  as a function of the true (input) value of  $\sin^2 2\theta \equiv \sin^2 2\theta_{23}$  (left panel) and  $\Delta m^2 \equiv \Delta m_{32}^2$  (right panel). The red solid lines are for Kamioka-Korea setting with each 0.27 Mton detector, while the dashed black (dotted blue) lines are for Kamioka (Korea) only setting with 0.54 Mton detector. The thick and the thin lines are for 99% and 90% CL, respectively. 4 years of neutrino plus 4 years of anti-neutrino running are assumed. The other input values of the parameters are identical to those in Fig. 3.

Kamioka-Korea setting is only slightly less by about 15 – 20%. Whereas, the sensitivity by the Korea-only setting is much worse, more than a factor of 2 compared to the Kamioka-only setting. The reason for this lies in the  $\nu_\mu$  and  $\bar{\nu}_\mu$  survival probabilities. In this scenario, the effect of the non-vanishing  $\delta b$  appears as the difference in the oscillation frequency between neutrinos and anti-neutrinos, if the energy dependence is neglected. In this case, the measurement at different baseline is not very important. Then the Kamioka-only setup turns out to be slightly better than the Kamioka-Korea setup. This case is also unique by having the worst sensitivity at the largest value of  $\Delta m^2$  (right panel). Also, the correlation of sensitivity to  $\sin^2 2\theta$  (left panel) is strongest among the cases examined in this paper, with maximal sensitivity at maximal  $\theta$ .

### C. Comparison between sensitivities of Kamioka-Korea setting and the existing bounds

We summarize the results of the previous subsections in Table II, along with the present bounds on  $\delta c$  and  $\delta b$ , respectively. We quote the current bounds on  $\delta c$ 's from Ref.s [38, 39] which was obtained by the atmospheric neutrino data,

$$|\delta c_{\mu\tau}| \lesssim 3 \times 10^{-26}. \quad (11)$$

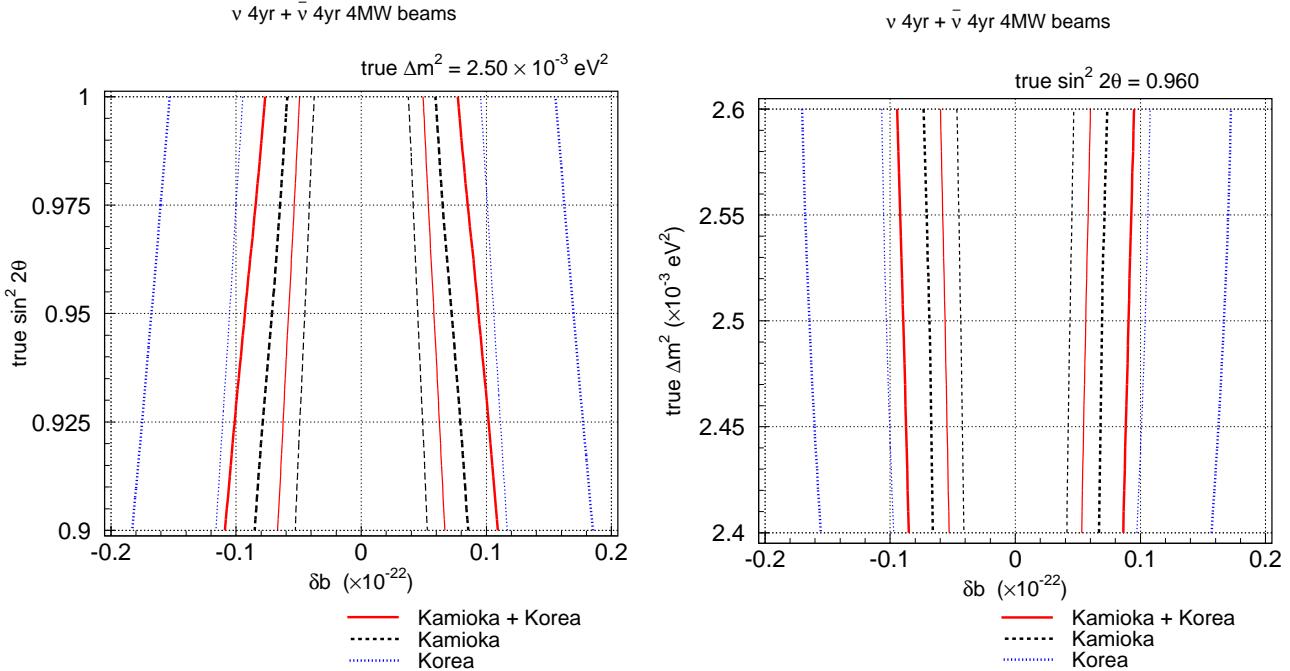


FIG. 5: The same as in Fig. 4 but for the case of non-vanishing  $\delta b$ .

We note that the current bound on  $\delta c_{\mu\tau}$  obtained by atmospheric neutrino data is quite strong. The reason why the atmospheric neutrino data give much stronger limit is that the relevant energy is much higher (typically  $\sim 100$  GeV) than the one we are considering ( $\sim 1$  GeV) and the baseline is larger, as large as the Earth diameter.

For the bound on  $\delta b$ , Barger et al. [40] argue that

$$|\delta b_{\mu\tau}| < 3 \times 10^{-20} \text{ GeV} \quad (12)$$

from the analysis of the atmospheric neutrino data. Let us compare the sensitivity on  $\delta b$  within our two detector setup with the sensitivity at a neutrino factory. Barger et al. [40] considered a neutrino factory with  $10^{19}$  stored muons with 20 GeV energy, and 10 kton detector, and concluded that it can probe  $|\delta b| < 3 \times 10^{-23}$  GeV. The Kamioka-Korea two detector setup and Kamioka-only setup have five and six times better sensitivities compared with the neutrino factory with the assumed configuration. Of course the sensitivity of a neutrino factories could be improved with a larger number of stored muons and a larger detector. A more meaningful comparison would be possible, only when one has configurations for both experiments which are optimized for the purposes of each experiment. Still we can conclude that the two-detector setup could be powerful to probe the Lorentz symmetry violation.

## VI. NONSTANDARD NEUTRINO INTERACTIONS WITH MATTER

It was suggested that neutrinos might have nonstandard neutral current interactions with matter [5, 6, 7, 41],  $\nu_\alpha + f \rightarrow \nu_\beta + f$  ( $\alpha, \beta = e, \mu, \tau$ ), with  $f$  being the up quarks, the down quarks and electrons. This effect may be described by a low energy effective Hamiltonian

LV parameters	Current bound	Kamioka-only	Korea-only	Kamioka-Korea
$ \delta c $	$\lesssim 3 \times 10^{-26}$	$\lesssim 5 \times 10^{-23}$	$\lesssim 4 \times 10^{-23}$	$\lesssim 3 \times 10^{-23}$
$ \delta b $ (GeV)	$< 3.0 \times 10^{-20}$	$\lesssim 1 \times 10^{-23}$	$\lesssim 0.5 \times 10^{-23}$	$\lesssim 0.6 \times 10^{-23}$

TABLE II: Presented are the upper bounds on the velocity mixing parameter  $\delta c$  and the CPT violating parameter  $\delta b$  (in GeV) for the case where  $\theta_m = \theta_b = \theta_c \equiv \theta$  and  $\eta = \eta' = 0$ . The current bounds are based on [38, 40] and are at 90% CL. The sensitivities obtained in this study are also at 90% CL and correspond to the true values of the parameters  $\Delta m^2 = 2.5 \times 10^{-3} \text{ eV}^2$  and  $\sin^2 2\theta_{23} = 0.96$ .

for new nonstandard interactions (NSI) of neutrinos:

$$H_{\text{NSI}} = 2\sqrt{2}G_F (\bar{\nu}_\alpha \gamma_\rho \nu_\beta) \left( \varepsilon_{\alpha\beta}^{ff'L} \bar{f}_L \gamma^\rho f'_L + \varepsilon_{\alpha\beta}^{ff'R} \bar{f}_R \gamma^\rho f'_R \right) + H.c. \quad (13)$$

where  $\varepsilon_{\alpha\beta}^f \equiv \varepsilon_{\alpha\beta}^{fL} + \varepsilon_{\alpha\beta}^{fR}$  and  $\varepsilon_{\alpha\beta}^{fP} \equiv \varepsilon_{\alpha\beta}^{fFP}$ . It is known that the presence of such NSI can affect production and/or detection processes of neutrinos as well as propagation of neutrinos in matter. In this work, for simplicity, we consider the impact of NSI only for propagation. By using  $\varepsilon_{\alpha\beta}$  defined as  $\varepsilon_{\alpha\beta} \equiv \sum_{f=u,d,e} \varepsilon_{\alpha\beta}^f n_f / n_e$ , the effects of NSI may be summarized by a term with dimensionless parameters  $\varepsilon_{\alpha\beta}$  in the effective Hamiltonian

$$H_{\text{eff}} = \sqrt{2}G_F N_e \begin{pmatrix} \varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon_{e\mu}^* & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon_{e\tau}^* & \varepsilon_{\mu\tau}^* & \varepsilon_{\tau\tau} \end{pmatrix} \quad (14)$$

which is to be added to the standard matter term  $\sqrt{2}G_F N_e \text{ diag.}(1, 0, 0)$  [5] in the evolution equation of neutrinos. Here,  $G_F$  is the Fermi constant,  $N_e$  denotes the averaged electron number density along the neutrino trajectory in the earth. The existing constraints on  $\varepsilon_{\alpha\beta}$  are worked out in [42, 43, 44]:

$$\begin{pmatrix} -0.9 < \varepsilon_{ee} < 0.75 & |\varepsilon_{e\mu}| \lesssim 3.8 \times 10^{-4} & |\varepsilon_{e\tau}| \lesssim 0.25 \\ -0.05 < \varepsilon_{\mu\mu} < 0.08 & |\varepsilon_{\mu\tau}| \lesssim 0.15 \\ & |\varepsilon_{\tau\tau}| \lesssim 0.4 \end{pmatrix}. \quad (15)$$

Note that the bounds on  $\varepsilon_{\mu\tau}$  and  $\varepsilon_{\tau\tau}$  are coming from atmospheric neutrino data [44] and LEP data [43], respectively, which are relatively weak and we wish to investigate how much we can improve these bounds at the Kamioka-Korea two detector setup.

In this work we truncate the system so that we confine into the  $\mu-\tau$  sector of the neutrino evolution. Then, the time evolution of the neutrinos in flavor basis can be written as

$$i \frac{d}{dt} \begin{pmatrix} \nu_\mu \\ \nu_\tau \end{pmatrix} = \left[ U \begin{pmatrix} 0 & 0 \\ 0 & \frac{\Delta m_{32}^2}{2E} \end{pmatrix} U^\dagger + a \begin{pmatrix} 0 & \varepsilon_{\mu\tau} \\ \varepsilon_{\mu\tau}^* & \varepsilon_{\tau\tau} - \varepsilon_{\mu\mu} \end{pmatrix} \right] \begin{pmatrix} \nu_\mu \\ \nu_\tau \end{pmatrix}, \quad (16)$$

where  $U$  is the flavor mixing matrix and  $a \equiv \sqrt{2}G_F N_e$ . In the 2-2 element of the NSI term in the Hamiltonian is of the form  $\varepsilon_{\tau\tau} - \varepsilon_{\mu\mu}$  because the oscillation probability depend upon  $\varepsilon$ 's only through this combination. The evolution equation for the anti-neutrinos are given by changing the signs of  $a$  and replacing  $U$  by  $U^*$ .

In fact, one can show that the truncation to the  $2 \times 2$  sub system is a good approximation. In the full three flavor framework the  $\nu_\mu$  disappearance oscillation probability can be computed to leading order of NSI as [45]

$$\begin{aligned}
P(\nu_\mu \rightarrow \nu_\mu) = & 1 - \sin^2 2\theta_{23} \sin^2 \Delta_{32} \\
& - |\varepsilon_{\mu\tau}| \cos \phi_{\mu\tau} \sin 2\theta_{23} (aL) \left[ \sin^2 2\theta_{23} \sin 2\Delta_{32} + \cos^2 2\theta_{23} \frac{2}{\Delta_{32}} \sin^2 \Delta_{32} \right] \\
& - \frac{1}{2} (\varepsilon_{\tau\tau} - \varepsilon_{\mu\mu}) \sin^2 2\theta_{23} \cos 2\theta_{23} (aL) \left[ \sin 2\Delta_{32} - \frac{2}{\Delta_{32}} \sin^2 \Delta_{32} \right] \\
& + \mathcal{O}\left(\frac{\Delta m_{21}^2}{\Delta m_{31}^2}\right) + \mathcal{O}(s_{13}) + \mathcal{O}(\varepsilon^2),
\end{aligned} \tag{17}$$

where  $\Delta_{32} \equiv \frac{\Delta m_{32}^2 L}{4E}$  and  $\phi_{\mu\tau}$  is the phase of  $\varepsilon_{\mu\tau}$ . The result in (17) indicates that the truncation is legitimate if  $\varepsilon$ 's are sufficiently small. Also note that the dependence on  $\varepsilon_{\tau\tau} - \varepsilon_{\mu\mu}$  goes away for  $\sin^2 \theta = 0.5$ , so that the muon disappearance becomes insensitive to this combination of  $\varepsilon$ 's. We will find that the sensitivity on  $\varepsilon_{\tau\tau} - \varepsilon_{\mu\mu}$  strongly depends on  $\sin^2 \theta$  ( $\theta$  being maximal or not) for this reason. In the following we set  $\varepsilon_{\mu\mu} = 0$  so that the sensitivity contours presented for  $\varepsilon_{\tau\tau}$  actually means those for  $\varepsilon_{\tau\tau} - \varepsilon_{\mu\mu}$ . Moreover, for simplicity, we assume that  $\varepsilon_{\mu\tau}$  is a real by ignoring its phase.

In Fig. 6, presented are the allowed regions in  $\varepsilon_{\mu\tau} - \varepsilon_{\tau\tau}$  space for 4 years neutrino and 4 years anti-neutrino running of the Kamioka-only (upper panels), the Korea-only (middle panels), and the Kamioka-Korea (bottom panels) settings. The input values  $\varepsilon_{\mu\tau}$  and  $\varepsilon_{\tau\tau}$  are taken to be vanishing.

As in the CPT-Lorentz violating case studied in Sec. VB and unlike the system with decoherence, the Korea-only setting gives much worse sensitivity compared to the other two settings. Again the Kamioka-only setting has a slightly better sensitivity than the Kamioka-Korea setting. However we notice that the Kamioka-only setting has multiple  $\varepsilon_{\tau\tau}$  solutions for  $\sin^2 \theta_{23} = 0.45$ . The fake solutions are nearly eliminated in the Kamioka-Korea setting.

The sensitivities of three experimental setups at  $2\sigma$  CL can be read off from Fig. 6. The approximate  $2\sigma$  CL sensitivities of the Kamioka-Korea setup for  $\sin^2 \theta = 0.45$  ( $\sin^2 \theta = 0.5$ ) are:

$$|\varepsilon_{\mu\tau}| \lesssim 0.03 \text{ (0.03)}, \quad |\varepsilon_{\tau\tau}| \lesssim 0.3 \text{ (1.2)}. \tag{18}$$

Here we neglected a barely allowed region near  $|\varepsilon_{\tau\tau}| = 2.3$ , which is already excluded by the current data. Note that the sensitivity on  $\varepsilon_{\tau\tau}$  becomes weak for maximal mixing ( $\sin^2 \theta = 0.5$ ), for the above mentioned reason (see Eq. (17) and the subsequent discussions). The Kamioka-Korea setup can improve the current bound on  $|\varepsilon_{\mu\tau}|$  by factors of  $\sim 5$  whereas the bound on  $|\varepsilon_{\tau\tau}|$  we obtained is comparable to (worse than) the current bound for  $\sin^2 \theta = 0.45$  ( $\sin^2 \theta = 0.5$ ). A similar statement applies to the case for the Kamioka-only setup.

There are a large number of references which studied the effects of NSI and the sensitivity reach to NSI by the ongoing and the various future projects. We quote here only the most recent ones which focused on sensitivities by superbeam and reactor experiments [45] and neutrino factory [46]. The earlier references can be traced back through the bibliography of these papers.

By combining future superbeam experiment, T2K [20] and reactor one, Double-Chooz [23], the authors of [45] obtained the sensitivity of  $|\varepsilon_{\mu\tau}|$  to be  $\sim 0.25$  when it is assumed to be real (no CP phase) while essentially no sensitivity to  $\varepsilon_{\tau\tau}$  is expected. The same authors

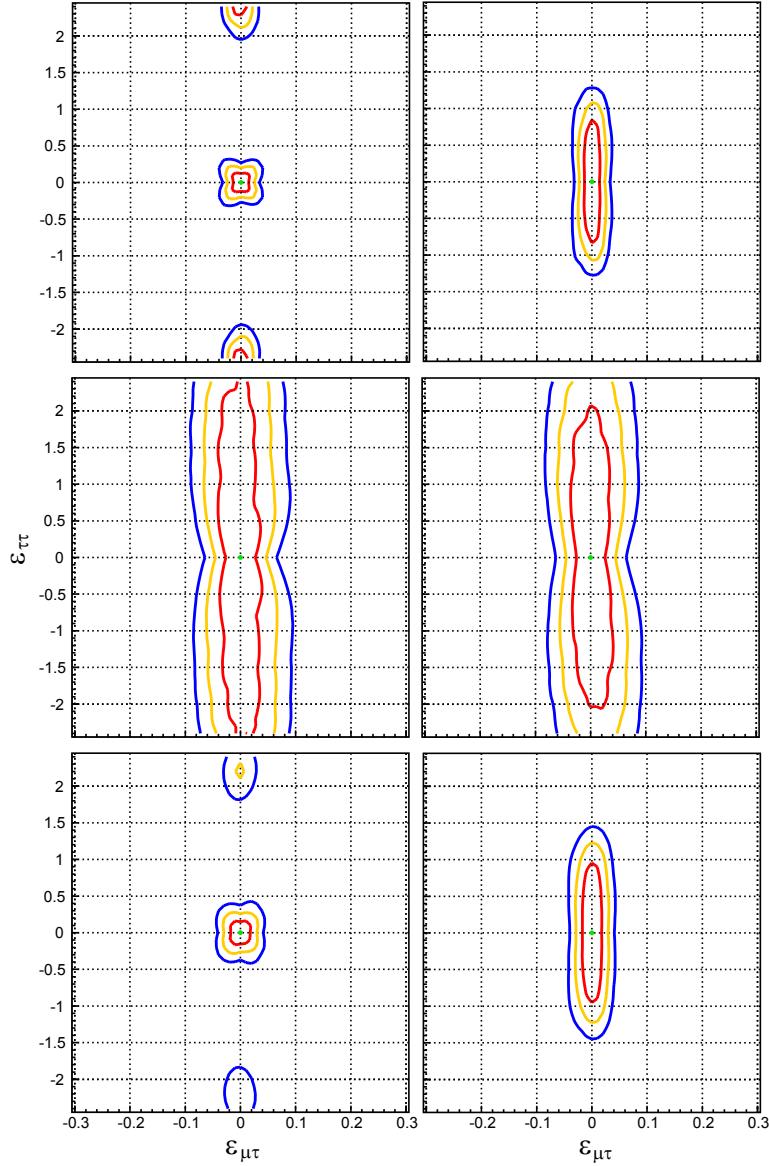


FIG. 6: The allowed regions in  $\epsilon_{\mu\tau} - \epsilon_{\tau\tau}$  space for 4 years neutrino and 4 years anti-neutrino running. The upper, the middle, and the bottom three panels are for the Kamioka-only setting, the Korea-only setting, and the Kamioka-Korea setting, respectively. The left and the right panels are for cases with  $\sin^2 \theta \equiv \sin^2 \theta_{23} = 0.45$  and 0.5, respectively. The red, the yellow, and the blue lines indicate the allowed regions at  $1\sigma$ ,  $2\sigma$ , and  $3\sigma$  CL, respectively. The input value of  $\Delta m_{32}^2$  is taken as  $2.5 \times 10^{-3}$  eV $^2$ .

also consider the case of NO $\nu$ A experiment [21] combined with some future upgraded reactor experiment with larger detector as considered, e.g., in [47, 48] and obtained  $\epsilon_{\mu\tau}$  sensitivity of about 0.05 which is comparable to what we obtained.

While essentially no sensitivity of  $\epsilon_{\tau\tau}$  is expected by superbeam, future neutrino factory with the so called golden channel  $\nu_e \rightarrow \nu_\mu$  and  $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$ , could reach the sensitivity to  $\epsilon_{\tau\tau}$  at

the level of  $\sim 0.1\text{--}0.2$  [46]. Despite that the sensitivity to  $\epsilon_{\mu\tau}$  by neutrino factory was not derived in [46], from Fig. 1 of this reference, one can naively expect that the sensitivity to  $\epsilon_{\mu\tau}$  is similar to that of  $\epsilon_{ee}$  which is  $\sim 0.1$  or so. We conclude that the sensitivity we obtained for  $\epsilon_{\mu\tau}$  is not bad.

## VII. CONCLUDING REMARKS

The Kamioka-Korea two detector system was shown to be a powerful setup for lifting neutrino parameter degeneracies and probing CP violation in neutrino oscillation. In this paper, we study sensitivities of this setup to nonstandard neutrino physics such as quantum decoherence, tiny violation of Lorentz symmetry, and nonstandard interactions of neutrinos with matter. In most cases, two detector setup is more sensitive than a single detector at Kamioka or Korea, except for the Lorentz violation with  $\delta b \neq 0$ , and the nonstandard neutrino interactions with matter. The sensitivities of three experimental setups at 90% CL are summarized in Table I and Table II for quantum decoherence and Lorentz symmetry violation with/without CPT symmetry, respectively. We can say that future long baseline experiments with two detector setup can improve the sensitivities on nonstandard neutrino physics in many cases. We believe that it is a useful addition to the physics capabilities of the Kamioka-Korea two-detector setting that are already demonstrated, namely, resolution of the mass hierarchy and resolving CP and the octant degeneracies.

### Acknowledgments

One of the authors (P.K.) is grateful to ICRR where a part of this research has been performed. Two of us (H.M. and H.N.) thank Theoretical Physics Department of Fermi National Accelerator Laboratory for hospitalities extended to them in the summer of 2007. This work was supported in part by KAKENHI, the Grant-in-Aid for Scientific Research, No. 19340062, Japan Society for the Promotion of Science, by Fundação de Amparo à Pesquisa do Estado de Rio de Janeiro (FAPERJ) and Conselho Nacional de Ciência e Tecnologia (CNPq), and by KOSEF through CHEP at Kyungpook National University.

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